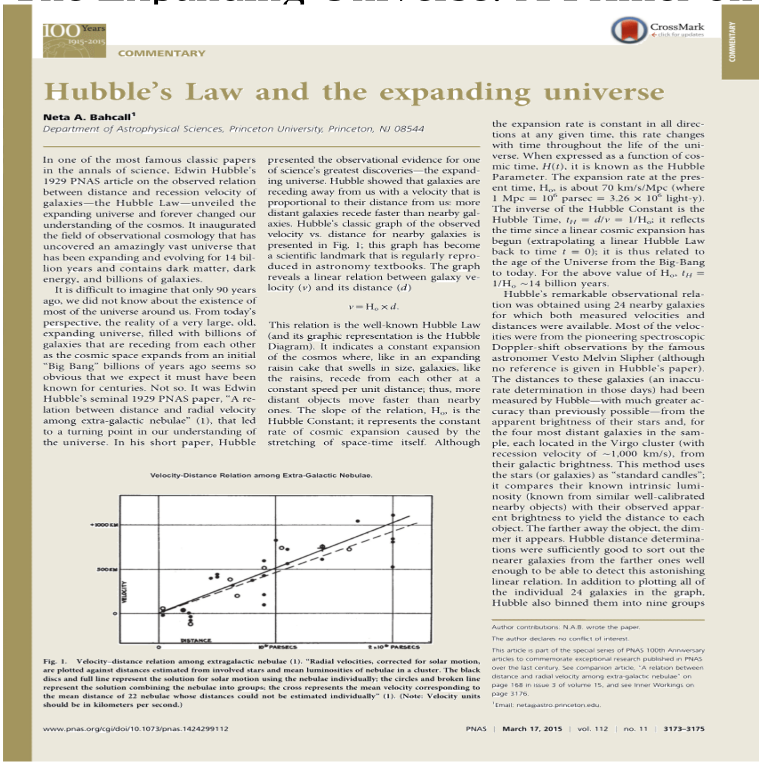
The Expanding Universe: A Primer on Relativistic Cosmology



100 Years 1915-2015

COMMENTARY

Hubble's Law and the expanding universe

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In one of the most famous classic papers in the annals of science, Edwin Hubble's 1929 PNAS article on the observed relation between distance and recession velocity of galaxies—the Hubble Law—unveiled the expanding universe and forever changed our understanding of the cosmos. It inaugurated the field of observational cosmology that has uncovered an amazingly vast universe that has been expanding and evolving for 14 billion years and contains dark matter, dark energy, and billions of galaxies.

It is difficult to imagine that only 90 years ago, we did not know about the existence of most of the universe around us. From today's perspective, the reality of a very large, old, expanding universe, filled with billions of galaxies that are receding from each other as the cosmic space expands from an initial "Big Bang" billions of years ago seems so obvious that we expect it must have been known for centuries. Not so. It was Edwin Hubble's seminal 1929 PNAS paper, "A relation between distance and radial velocity among extra-galactic nebulae" (1), that led to a turning point in our understanding of the universe. In his short paper, Hubble presented the observational evidence for one of science's greatest discoveries—the expanding universe. Hubble showed that galaxies are receding away from us with a velocity that is proportional to their distance from us: more distant galaxies recede faster than nearby galaxies. Hubble's classic graph of the observed velocity vs. distance for nearby galaxies is presented in Fig. 1; this graph has become a scientific landmark that is regularly reproduced in astronomy textbooks. The graph reveals a linear relation between galaxy velocity (v) and its distance (d)

$$v = H_o \times d.$$

This relation is the well-known Hubble Law (and its graphic representation is the Hubble Diagram). It indicates a constant expansion of the cosmos where, like in an expanding raisin cake that swells in size, galaxies, like the raisins, recede from each other at a constant speed per unit distance; thus, more distant objects move faster than nearby ones. The slope of the relation, H_o, is the Hubble Constant; it represents the constant rate of cosmic expansion caused by the stretching of space-time itself. Although the expansion rate is constant in all directions at any given time, this rate changes with time throughout the life of the universe. When expressed as a function of cosmic time, $H(t)$, it is known as the Hubble Parameter. The expansion rate at the present time, H_o, is about 70 km/s/Mpc (where 1 Mpc = 10^6 parsec = 3.26×10^6 light-y). The inverse of the Hubble Constant is the Hubble Time, $t_H = d/v = 1/H_o$; it reflects the time since a linear cosmic expansion has begun (extrapolating a linear Hubble Law back to time $t = 0$); it is thus related to the age of the Universe from the Big-Bang to today. For the above value of H_o, $t_H = 1/H_o \sim 14$ billion years.

Hubble's remarkable observational relation was obtained using 24 nearby galaxies for which both measured velocities and distances were available. Most of the velocities were from the pioneering spectroscopic Doppler-shift observations by the famous astronomer Vesto Melvin Slipher (although no reference is given in Hubble's paper). The distances to these galaxies (an inaccurate determination in those days) had been measured by Hubble—with much greater accuracy than previously possible—from the apparent brightness of their stars and, for the four most distant galaxies in the sample, each located in the Virgo cluster (with recession velocity of ~1,000 km/s), from their galactic brightness. This method uses the stars (or galaxies) as "standard candles"; it compares their known intrinsic luminosity (known from similar well-calibrated nearby objects) with their observed apparent brightness to yield the distance to each object. The farther away the object, the dimmer it appears. Hubble distance determinations were sufficiently good to sort out the nearer galaxies from the farther ones well enough to be able to detect this astonishing linear relation. In addition to plotting all of the individual 24 galaxies in the graph, Hubble also binned them into nine groups

Velocity-Distance Relation among Extra-Galactic Nebulae.

Fig. 1. Velocity–distance relation among extragalactic nebulae (1). "Radial velocities, corrected for solar motion, are plotted against distances estimated from involved stars and mean luminosities of nebulae in a cluster. The black discs and full line represent the solution for solar motion using the nebulae individually; the circles and broken line represent the solution combining the nebulae into groups; the cross represents the mean velocity corresponding to the mean distance of 22 nebulae whose distances could not be estimated individually" (1). (Note: Velocity units should be in kilometers per second.)

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This article is part of the special series of PNAS 100th Anniversary articles to commemorate exceptional research published in PNAS over the last century. See companion article, "A relation between distance and radial velocity among extra-galactic nebulae" on page 168 in issue 3 of volume 15, and see Inner Workings on page 3176.

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